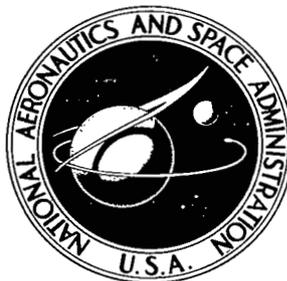


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SOLAR ABSORPTANCES AND SPECTRAL REFLECTANCES OF 12 METALS FOR TEMPERATURES RANGING FROM 300 TO 500 K

*by Ernie W. Spisz, Albert J. Weigand,
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

The solar absorptance of 12 metals (Al, Cu, Au, Mo, Ni, Pt, Ag, stainless steel 304, Ta, Sn, Ti, and V) were determined over the temperature range from 250 to 550 K by two different experimental methods. Direct measurements of solar absorptance were made with a cyclic radiation method using a high intensity carbon arc solar simulator. Indirect measurements of solar absorptance were obtained from spectral reflectance measurements obtained from an integrating sphere reflectometer over the wavelength range from 0.33 to 2.16 μm . The solar absorptance data as obtained from the two different methods as well as the spectral reflectance data are presented for the 12 metals.

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SUMMARY

The solar absorptance of 12 different metals (aluminum, copper, gold, molybdenum, nickel, platinum, silver, stainless steel 304, tantalum, tin, titanium, and vanadium) was determined by direct and indirect measurements over the temperatures from 250 to 550 K. The direct measurements were made by a cyclic radiation method and the indirect measurements by integrating sphere reflectometer measurements of spectral reflectance. The absorptance determined by the two different methods agreed to within ± 10 percent. The solar absorptance was practically independent of temperature over the temperature range from 250 to 550 K.

The spectral reflectance (angular-hemispherical) of the materials as determined by the integrating sphere reflectometer method is also presented for the wavelength range from 0.33 to 2.16 micrometers. The effects of sphere wall uniformity, polarization, and monochromator slit width were considered and found to be of minor importance. The integrating sphere reflectometer method for determining solar absorptance of high reflectance, specular samples was both convenient and expedient. However, extreme care in procedure and in the use of the experimental equipment was required to obtain accurate absorptance data because small errors in reflectance measurements could introduce large errors in solar absorptance.

INTRODUCTION

The thermal analyses of spacecraft components for advanced missions out of earth orbit require accurate thermal radiation property data for a variety of materials. For these types of missions the luxury of conservative design often does not exist, and predictions of component temperatures must be made as accurately as possible. The

solar absorptance and spectral reflectance are property data that are of primary importance for thermal analyses because solar energy is the major heat load to many spacecraft components.

Various experimental methods are available for determining solar absorptance of materials (ref. 1); however, it is difficult to establish the accuracy of the data obtained from a specific method. For example, there are many different methods being used that measure solar absorptance directly, all requiring a radiant source for simulating the solar energy spectrum. Most sources have only fair fidelity, are at best only approximations to the solar energy spectrum, and thus can introduce systematic errors into the experimental data.

Indirect methods of measuring solar absorptance generally measure spectral reflectance and thereby eliminate the need for a simulation source. However, extreme care must be exercised in the accurate measurement of spectral reflectance. Small errors in spectral reflectance can result in large errors in solar absorptance (especially for high reflectance materials).

The objective of this report is to present and compare the solar absorptance of 12 metals (aluminum, copper, gold, molybdenum, nickel, platinum, silver, stainless steel 304, tantalum, tin, titanium, and vanadium) obtained by a direct and an indirect method of measurement over the temperature range from 250 to 550 K. The direct method of solar absorptance measurement is the cyclic radiation technique of reference 2, which measures the absorptance of metals for the radiant energy from a high intensity carbon arc solar simulator. A detailed description of the experimental technique and the solar absorptance data obtained on metals with this method have been previously published in reference 3. A brief description of the direct technique is included for convenience.

The indirect method used for solar absorptance measurement is the integrating sphere reflectometer method of reference 4, which measures spectral reflectance from which the solar absorptance is determined. A description of the integrating sphere reflectometer method is presented, and the spectral reflectance data obtained on the various metals are presented over the wavelength range from 0.33 to 2.16 micrometers. The effect of sphere wall uniformity, monochromator slit width, and the influence of polarization of the monochromator beam on reflectance measurements are also illustrated.

CYCLIC RADIATION METHOD

The direct method used to determine solar absorptance (refs. 2 and 3) consists of suspending a thin metal sample in an ultra high vacuum, cold-wall environment. A radiant intensity I_0 from a carbon arc solar simulator is imposed normal to one sur-

face of the sample to establish an equilibrium temperature T_m . The radiant intensity is then perturbed sinusoidally with amplitude KI_0 (where $K < 1.0$) and frequency ω . Within the temperature range resulting from this intensity perturbation, the linearized solution for the sample temperature is

$$T = T_m + A \left[\sin(\omega t - \varphi) + e^{-(t/\theta')} \sin \varphi \right] \quad (1)$$

At cyclic equilibrium, the sample temperature is sinusoidal about T_m , with a temperature amplitude A and phase angle φ which lags the sinusoidal radiant intensity. The phase angle is given by

$$\varphi = \tan^{-1} \omega \theta' \quad (2)$$

and the temperature amplitude by

$$A = \left(\frac{\alpha K I_0}{m c_p} \right) \left[\left(\frac{1}{\theta'} \right)^2 + \omega^2 \right]^{-1/2} \quad (3)$$

where θ' , the time constant of the sample material, is

$$\theta' = \frac{m c_p}{8 \epsilon \sigma T_m^3} \quad (4)$$

where m is the weight per surface area, c_p is the material specific heat, ϵ is the emittance of the sample, and σ is the Stefan-Boltzman constant. Thus by measuring the phase angle and temperature amplitude at cyclic equilibrium, the absorptance of the sample can be determined from equation (3).

INTEGRATING SPHERE REFLECTOMETER METHOD

The integrating sphere reflectometer method is not a new method, but the specific technique, experimental apparatus, and procedure used herein require a brief description in order that the data may be interpreted correctly.

Method

The integrating sphere method measures the absolute, spectral, hemispherical reflectance of a sample for a near normal (approximately 15° off normal) incident beam of radiant energy. (The measured reflectance is approximately the normal hemispherical reflectance.) From the measured spectral reflectance ρ , the spectral absorptance $\alpha(\lambda)$ is

$$\alpha(\lambda) = 1 - \rho(\lambda) \quad (5)$$

and the solar absorptance α_s is

$$\alpha_s = \frac{\int_0^\infty \alpha(\lambda) J_s(\lambda) d\lambda}{\int_0^\infty J_s(\lambda) d\lambda} \quad (6)$$

where $J_s(\lambda)$ is the solar spectral irradiance at wavelength λ .

The evaluation of equation (6) was handled numerically by dividing the solar energy spectrum into N wavelength intervals such that the incremental solar energy ($dE = J_s(\lambda)d\lambda$) within each of the wavelength intervals is constant. Thus, for N equal energy wavelength intervals, the numerical approximation of equation (6) is

$$\alpha_s \approx \frac{\sum_{i=1}^{i=N} \bar{\alpha}_i(\lambda) (dE)_i}{\sum_{i=1}^{i=N} (dE)_i} = \frac{1}{N} \sum_{i=1}^{i=N} \bar{\alpha}_i(\lambda) \quad (7)$$

where $\bar{\alpha}_i(\lambda)$ is the average spectral absorptance over a given wavelength interval.

The value of N used herein is 50, so that the incremental energy in each interval corresponded to 2 percent of the total solar energy. The solar energy distribution of reference 5 was used to establish the wavelength intervals (see fig. 1). However, due to limitations of the experimental equipment, the reflectance at only 47 of the wavelength intervals could be measured. The reflectance could not be measured in the interval below 0.316 micrometer and for the two intervals beyond 2.30 micrometers. For the 47 wavelength intervals over which data are measured, the solar absorptance is determined by

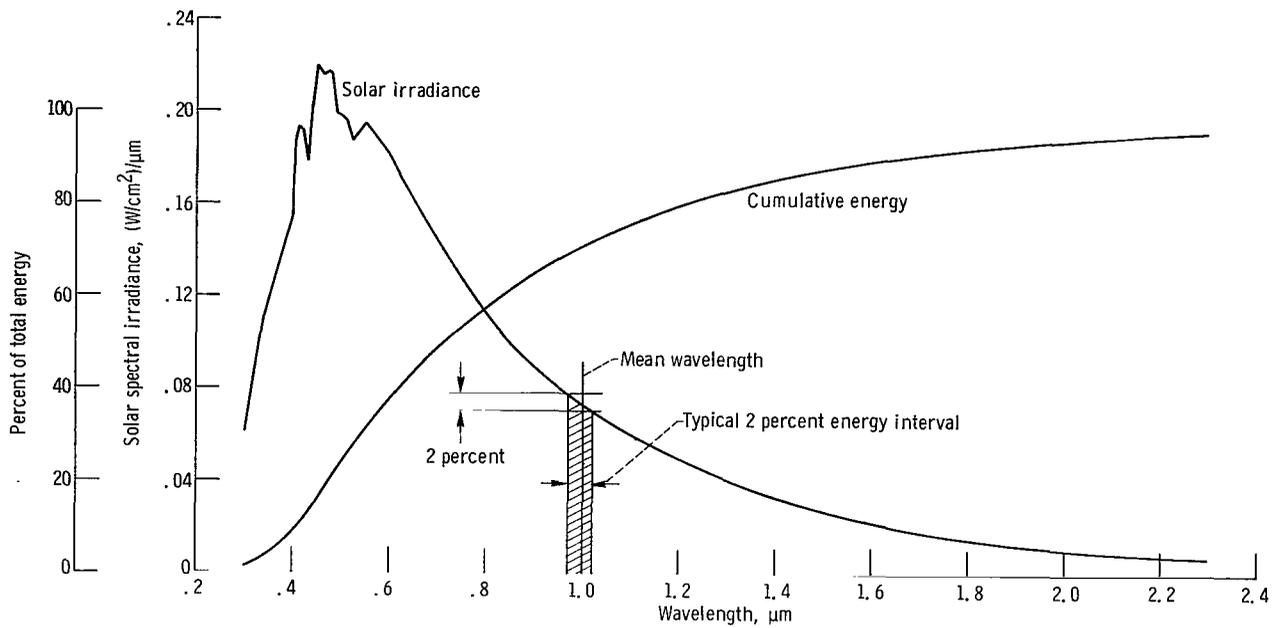
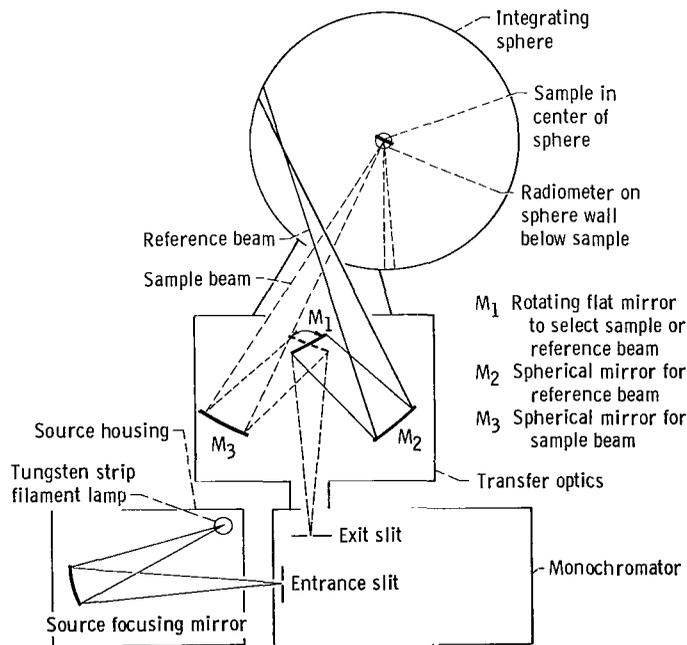


Figure 1. - Solar energy distribution curve (ref. 5).



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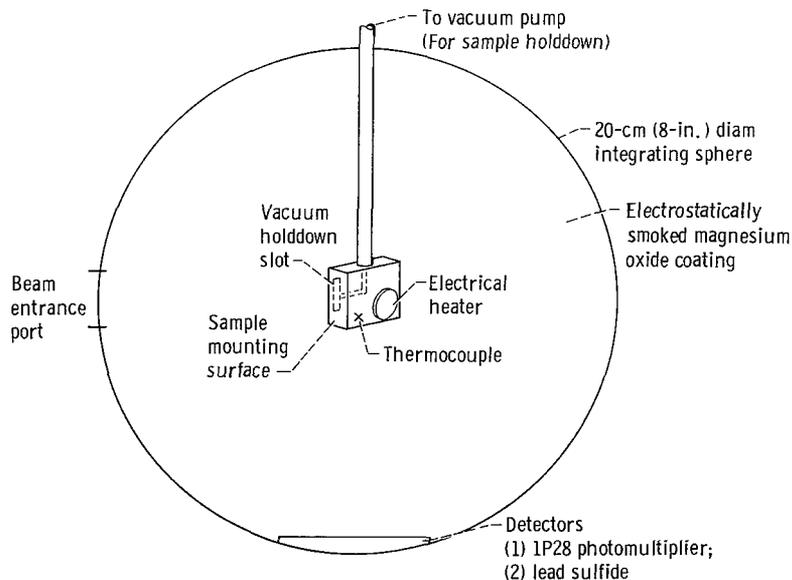
Figure 2. - Experimental arrangement for integrating sphere reflectometer.

$$\alpha_s = 0.0213 \sum_{i=1}^{i=47} \bar{\alpha}_i(\lambda) \quad (8)$$

Apparatus

The experimental arrangement used for the measurement of reflectance is shown schematically in figure 2. The system consists of a light source, monochrometer, transfer optics section, and integrating sphere. The light source is a tungsten strip filament lamp with optics to focus the source image onto the entrance slit of the monochrometer. The monochrometer is a single beam, double-pass, lithium fluoride prism instrument. The transfer optics section consists of a rotatable flat mirror and two spherical focusing mirrors that permit the beam from the monochrometer to be incident alternately on the sample and the sphere wall. The 20-centimeter (8-in.) diameter integrating sphere is commercially available (ref. 4). The sphere coating is electrostatically smoked magnesium-oxide, approximately 2-millimeter thick.

The schematic drawing in figure 3 shows the centrally located sample mounting block and the detectors on the sphere wall. The sample mounting block positions the sample in the center of the sphere so that the first reflection from the sample is incident on the sphere wall rather than directly on the detector. The sample mounting block is made of copper on which a button heater is mounted in order to heat the block, and sub-



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Figure 3. - Sphere and sample mounting.

sequently the sample, to temperatures up to 573 K. A copper constantan thermocouple is attached to the mounting block for temperature measurement. The stem of the mounting block is 0.63-centimeter (0.25-in.) diameter stainless-steel tubing which is connected to a vacuum pump to provide a vacuum holddown for the samples.

Two radiometers, a 1P28 photomultiplier tube and a lead sulfide detector, are used. The photomultiplier tube covers the wavelength range from 0.33 to 0.665 micrometer, and the lead sulfide detector covers the range from 0.63 to 2.16 micrometers.

Experimental Procedure

The spectral reflectance values are determined by the ratio of (1) the detector signal with the incident beam from the monochrometer focused on the sample and (2) the detector signal with the incident beam focused on the magnesium oxide walls of the sphere. Forty-seven reflectance values are determined for each sample at the wavelength corresponding to the mean wavelength of each wavelength interval. In order to obtain an average reflectance value over the wavelength interval of interest, the monochrometer slit width (or instrument band pass) is adjusted to correspond to the 2-percent energy interval as determined by the dispersion characteristics of the monochrometer (i. e., the slit width is varied for each spectral reflectance measurement). The monochrometer slit width is calculated by (ref. 6).

$$S = \frac{8f \sin\left(\frac{\beta}{2}\right) \left(\frac{dn}{d\lambda}\right) \Delta\lambda}{\left[1 - n^2 \sin^2\left(\frac{\beta}{2}\right)\right]^{1/2}} \quad (9)$$

where $\Delta\lambda$ is the wavelength for each 2-percent energy band, n is the refractive index of the lithium fluoride prism, f is the focal length (26.7 cm) of the parabolic spectrometer mirror, β is the lithium fluoride prism apex angle, and $dn/d\lambda$ is the linear dispersion of the double-pass monochrometer with a lithium fluoride prism.

Data were obtained initially for each sample at room temperature and 373 K. Data were then obtained for all of the samples at 473 K, and, finally, data were obtained for aluminum, gold, molybdenum, and platinum at a temperature above 473 K. During the course of the experimental program, the uniformity of the magnesium oxide coating on the sphere wall was periodically checked by scanning the sphere surface to ensure that large deviations in wall uniformity did not occur.

Samples

The samples used for the integrating sphere method were the same samples used in the cyclic radiation technique. The sample size is approximately 1- by 2- by 0.00254-centimeter thick. The materials are of high purity (99.99⁺ percent) but have only an as-received surface finish. No attempt was made to improve the surface finish of the samples. The only precautions taken were to clean the surface with a freon, detergent, and distilled water rinse to remove surface grime.

RESULTS

The solar absorptance data for the 12 different metals as measured by both the cyclic technique and the integrating sphere method are tabulated in table I and compared in figure 4. There is generally good agreement between the data of the two methods over the entire temperature range except for the copper sample and, to some extent, for platinum. For the most part, the data from the two methods agree to within ± 10 percent over the entire temperature range.

The data from both methods indicate that there is little effect of temperature on solar absorptance over the temperature range covered.

Even though the data from the two experimental methods do not exactly agree, the comparison to within ± 10 percent is considered quite good and indicates that, with proper care, either method can be used to provide useful data. The cyclic radiation method has the decided advantage that absorptance data can be obtained directly over a wide temperature range with better than 2-percent resolution. However, a stable, cyclically controlled simulated solar energy source is required. The integrating sphere reflectometer method is convenient and expedient for room temperature reflectance determinations, but extreme care is required in experimental procedure because small reflectance errors can result in large absorptance error.

The spectral reflectance data obtained from the integrating sphere method for each of the 12 metals are tabulated in table II. The data for aluminum, gold, and platinum are shown in figure 5 for room temperature and the highest temperature to illustrate the wavelength variation and the effect of temperature. The reflectance data are high in the infrared and, except for aluminum, decrease abruptly as the wavelength decreases toward the near ultraviolet wavelengths. The effect of temperature on reflectance is generally small. There is a consistent trend for reflectance to increase with increasing temperature in the visible wavelengths and to decrease with increasing temperature in the infrared wavelengths.

For comparison purposes, the reflectance data from reference 1 for normal incidence of freshly evaporated mirror coatings at room temperature are also included in

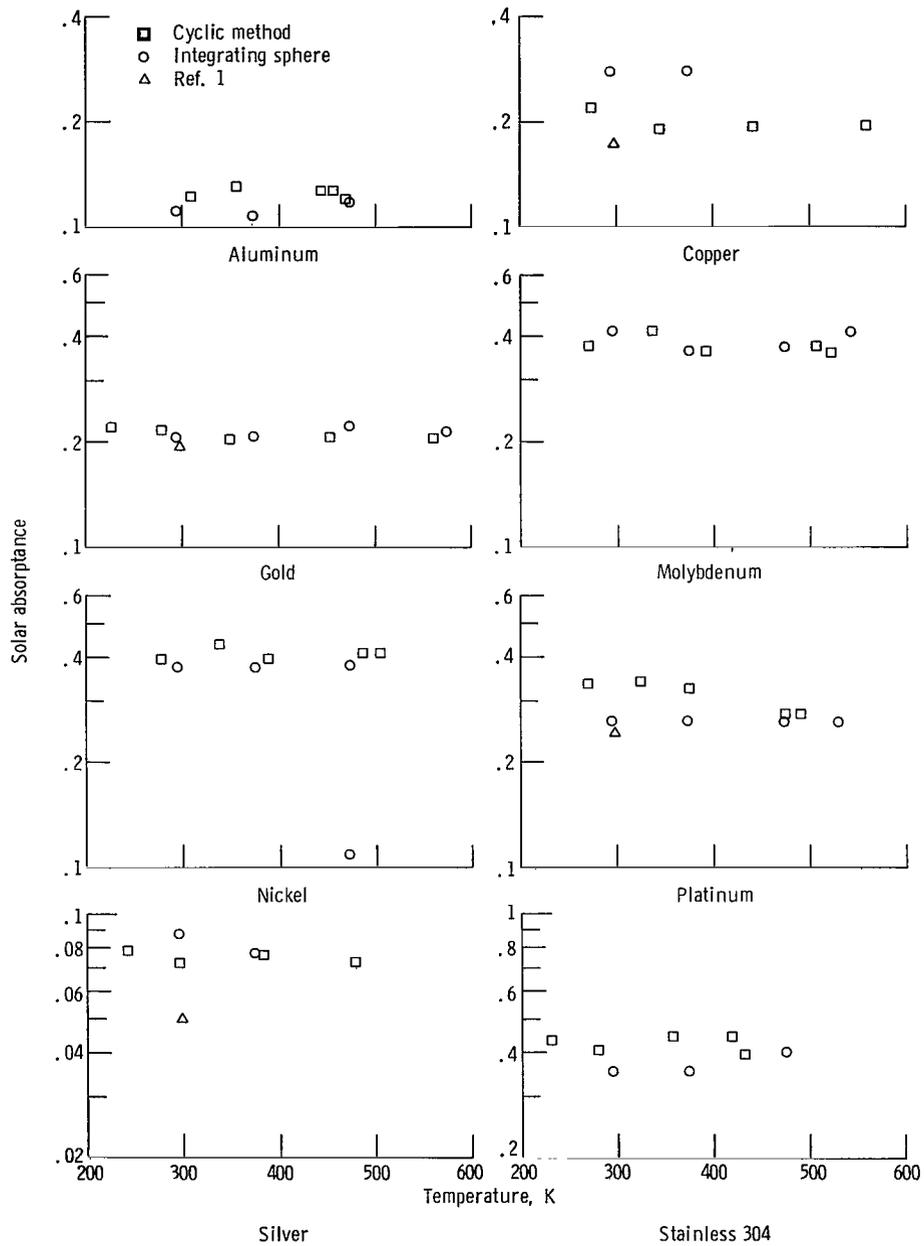


Figure 4. - Solar absorptance.

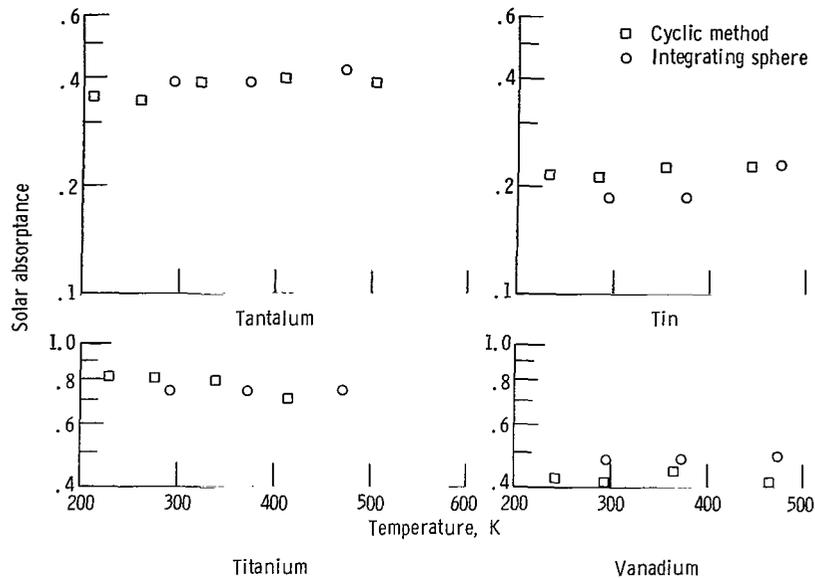


Figure 4. - Concluded.

figure 5. The overall spectral comparison is qualitatively good except in the visible wavelength region where the freshly evaporated mirror coatings have higher reflectance values.

DISCUSSION

The reasonably good agreement in measured solar absorptance between the two methods for the 12 metals tends to increase the confidence in both methods. The differences between the data from the two methods are probably due to changes in the sample surface, random experimental errors, differences between the carbon arc lamp spectral distribution and the solar energy spectrum, and the numerical integration required in the integrating sphere method. The changes in the sample surface are believed to account for most of the differences between the absorptance data from the two methods. Even though the same samples were used in both methods, a time period of approximately 3 months elapsed between the two programs. No special storage precautions were taken during this period except to store the samples in plastic bags. The freon, detergent, distilled water washing given to each sample before obtaining data served mainly to remove surface dirt and handling marks. The possibility of a difference in surface oxidation, however, still exists, especially for copper, as indicated by the much higher absorptance as determined by the integrating sphere method.

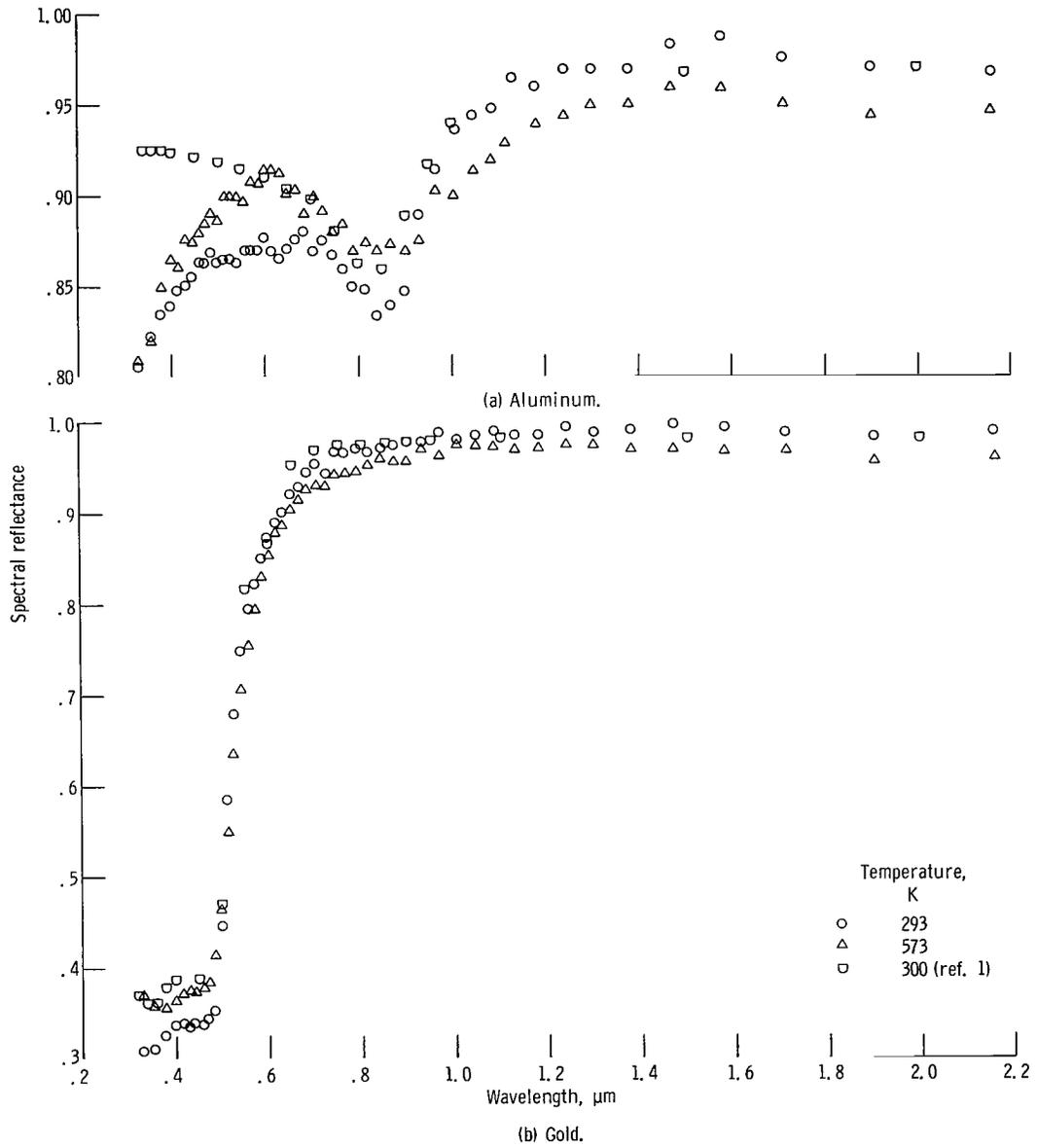
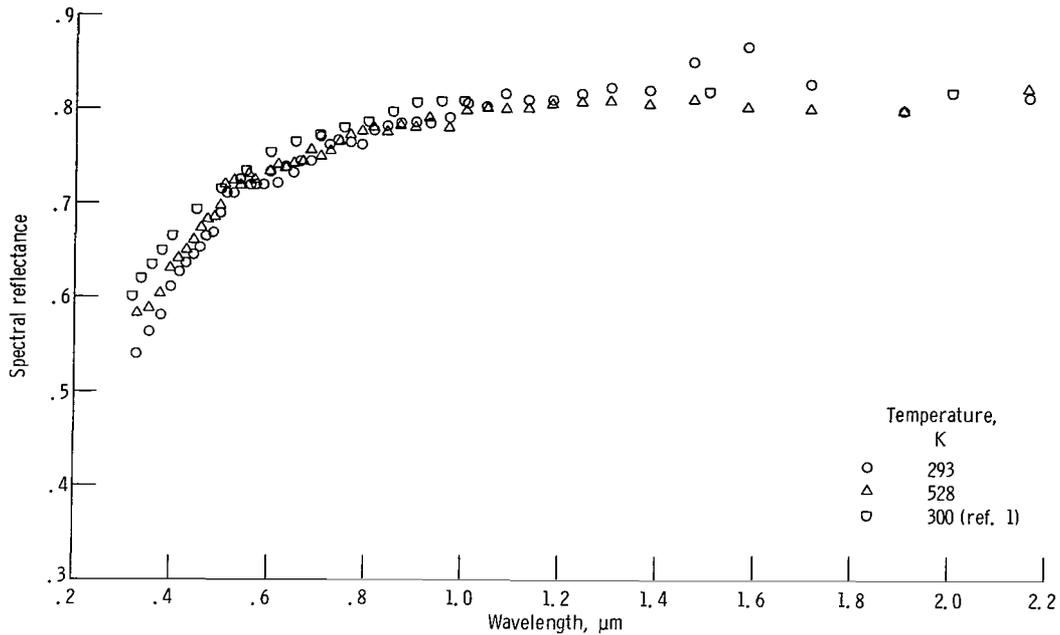


Figure 5. - Spectral reference data obtained by integrating sphere method.



(c) Platinum.

Figure 5. - Concluded.

Heating the samples to temperatures above 473 K in the atmosphere did not appear to increase surface oxidation on any of the samples except copper. Rapid oxidation of the copper sample at a temperature of 473 K resulted in a significant decrease in reflectance (as indicated by the data in table II) and a corresponding large increase in solar absorptance.

The effect of the difference between the spectral distribution of the carbon arc solar simulator and the solar energy spectrum was investigated for aluminum and platinum. The carbon arc absorptance was calculated by integrating the product of the metal spectral reflectance and the spectral irradiance of the carbon arc simulator over the wavelength range from 0.361 to 2.10 micrometers. The calculated carbon arc absorptance for aluminum and platinum was 0.106 and 0.258, respectively, as compared with values of 0.110 and 0.261 calculated for the solar energy spectrum. For metals, the carbon arc therefore appears to provide a reasonable approximation to the solar energy spectrum for solar absorptance determination.

The accuracy of the integrating sphere method to provide absolute reflectance data is difficult to assess. Many attempts to evaluate the errors associated with integrating spheres have been made (refs. 7 to 11). However, the results are difficult to interpret and apply to the particular sphere and sample mounting technique used herein. With proper sphere preparation and experimental technique, reference 4 estimates the error in reflectance to be ± 1.5 percent. For the high reflectance of the metal samples considered,

the corresponding error in absorptance

$$\frac{\delta(\alpha)}{\alpha} = \left(\frac{1 - \alpha}{\alpha} \right) \frac{\delta(\rho)}{\rho}$$

could be considerably higher. Of the possible sources of error that can occur with the integrating sphere method, the nonuniformity of the magnesium oxide sphere coating is probably the most serious. During the course of the experimental program, the uniformity of sphere coating was checked periodically by scanning the sphere wall. The wall uniformity was within ± 2 percent. Figure 6 presents a qualitative evaluation of the effect of sphere wall uniformity on absorptance. This figure is a comparison of the spectral reflectance of molybdenum for the incident beam from the monochromometer striking the sphere wall at two different locations approximately 90° apart. The reflectance data in figure 6 indicates that there is a slight effect on reflectance due to the location of the incident beam on the sphere wall but the reflectance data reproduce to within 1.5 percent. The calculated solar absorptance for these two conditions are

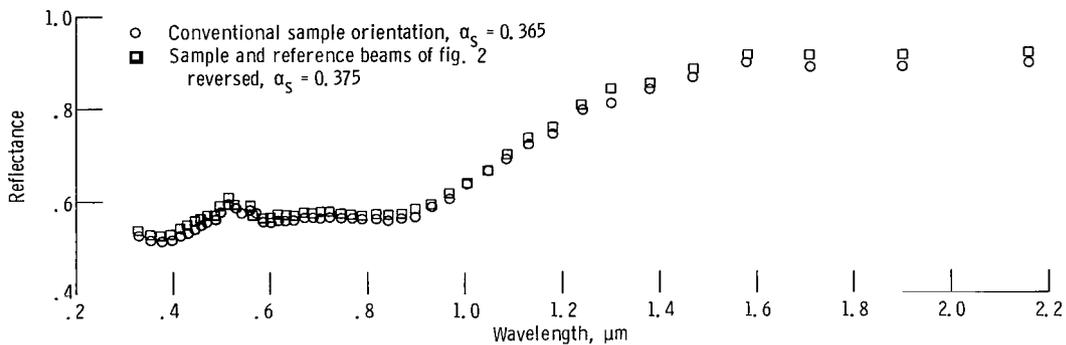


Figure 6. - Effect of sphere wall uniformity on reflectance data for molybdenum sample.

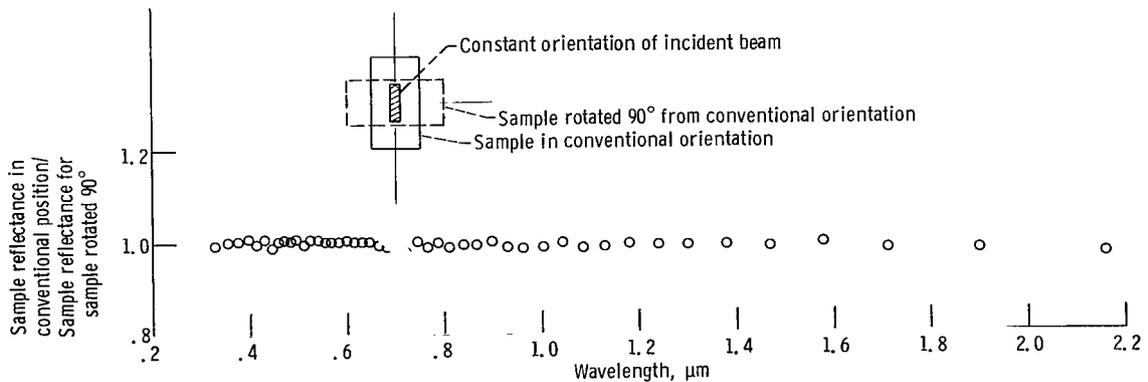


Figure 7. - Effect of incident beam polarization on reflectance of aluminum sample.

0.365 and 0.375, which is probably within the accuracy of the method.

Another possible sphere error is a result of polarization of the incident beam from the monochrometer. The effect of polarization is determined by a comparison of the reflectance measured (1) in the conventional sample orientation and (2) with the sample rotated 90° with respect to the plane of the incident beam (ref. 4). Figure 7 shows the effect of polarization on an aluminum sample. The indicated polarization effect on spectral reflectance is relatively small but there does appear to be an effect which is increasing with increasing wavelength. The comparatively small effect due to polarization, even though the incident beam from the monochrometer is highly polarized, is not too surprising because of the near normal incidence angle used throughout the investigation. It cannot be conclusively shown that the effect shown in figure 7 is really polarization rather than a nonuniformity across the sample surface.

A final possible source of error that was investigated was the effect of monochrometer slit width. In order to obtain an average reflectance value over the wavelength interval of interest, the slit width was varied for each wavelength as given by equation (9) and the dispersion of the monochrometer. However, it was of interest to determine whether the slit width and band pass would effect the reflectance measurements. Figure 8 is a comparison of the spectral reflectance of molybdenum for constant slit width of 0.25, 0.50, 1.0, and 2.0 millimeters. The data indicate that the monochrometer slit width has very little effect on the spectral reflectance of metals. Since the spectral reflectance of metals is smoothly varying without strong absorption bands, the average reflectance over a wavelength interval will be the same regardless of the wavelength interval. There is a noticeable increase in reflectance for the largest slit width of 2 millimeters over the wavelength range from 0.9 to 1.2 micrometers. The

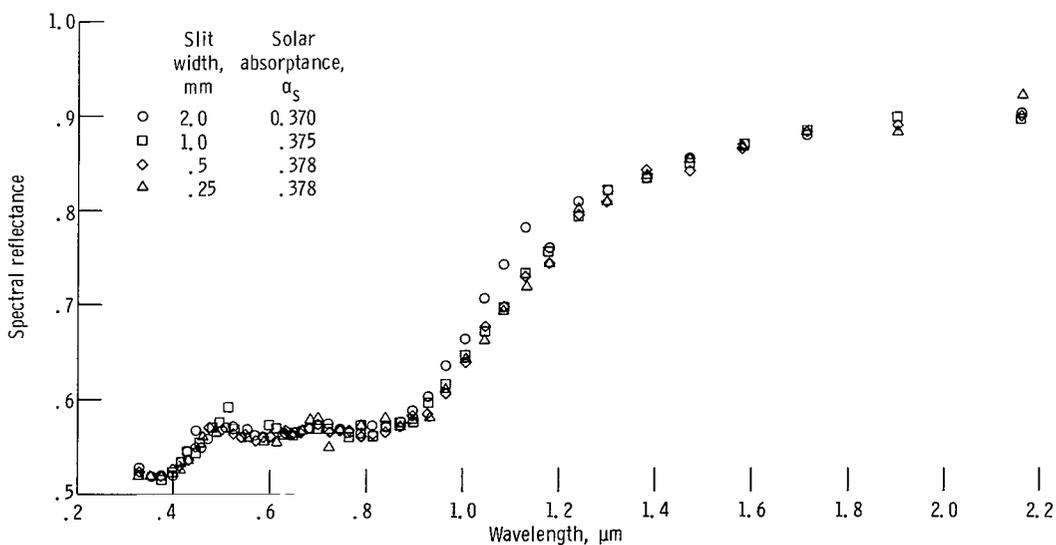


Figure 8. - Effect of monochrometer slit width on reflectance of molybdenum sample.

increase is more likely due to detector saturation at the high energy levels, rather than slit width. Considerable care was required throughout the experimental procedure to ensure that detector saturation did not occur. Actually, during a given spectral scan, it was necessary, at times, to reduce the energy of the incident beam by reducing the current to the tungsten filament source to prevent detector saturation.

Numerous spot checks made throughout the course of the program indicated the repeatability of the reflectance data to be within ± 1 percent. Occasionally, difficulties were experienced with detector or electronic noise, however, these effects were intermittent and data were taken only when measurements could be made with a precision of better than ± 1 percent.

CONCLUSIONS

Solar absorptance data were obtained by a direct measurement and an indirect spectral reflectance measurement for 12 metals with as-received surfaces over the temperature range from 250 to 550 K. The agreement between the two methods is within ± 10 percent over the temperature range covered. The solar absorptance is practically independent of temperature over the temperature range covered. The good agreement of the data from the two methods indicates that with proper technique either method can be used to provide useful absorptance data.

Spectral reflectance data obtained by the integrating sphere reflectometer method are also presented for the 12 metals for the wave range from 0.33 to 2.16 micrometers. The effect of temperature on spectral reflectance is small, but there is a slight increase in reflectance with increasing temperature in the visible wavelength range and a decrease in reflectance with increasing temperature in the infrared wavelength.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 5, 1969,
124-09-18-04-22.

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TABLE I. - SOLAR ABSORPTANCE OF METALS

Method				Method			
Integrating sphere reflectometer		Cyclic radiation		Integrating sphere reflectometer		Cyclic radiation	
Temperature, K	Absorptance	Temperature, K	Absorptance	Temperature, K	Absorptance	Temperature, K	Absorptance
Aluminum				Silver			
294	0.110	309	0.123	294	0.087	241	0.078
373	.107	355	.131	373	.077	296	.072
473	.118	393	.126	473	.109	382	.076
573	.101	455	.126	---	----	477	.073
---	----	469	.120	Stainless steel 304			
Copper				294	0.354	230	0.433
294	0.278	272	0.219	373	.356	278	.406
373	.279	345	.191	47 ^a	.403	357	.446
^a 473	.468	442	.194	---	----	417	.445
---	----	558	.196	---	----	432	.392
Gold				Tantalum			
294	0.207	227	0.221	294	0.389	212	0.353
373	.208	278	.217	373	.389	259	.343
473	.223	348	.205	473	.419	322	.388
573	.214	452	.206	---	----	409	.397
---	----	560	.205	---	----	502	.385
Molybdenum				Tin			
294	0.414	269	0.378	294	0.186	234	0.215
373	.364	335	.417	373	.186	286	.211
473	.375	392	.363	473	.230	352	.224
540	.416	504	.376	---	----	442	.228
---	----	522	.360	Titanium			
Nickel				294	0.719	231	0.811
294	0.372	278	0.395	373	.718	277	.80
373	.371	338	.437	473	.722	340	.793
473	.380	388	.395	---	----	415	.703
---	----	486	.410	Vanadium			
---	----	503	.408	294	0.478	242	0.425
Platinum				373	.478	294	.413
294	0.261	270	0.333	473	.492	366	.441
373	.260	325	.339	---	----	464	.416
473	.260	376	.324				
528	.259	474	.272				
---	----	489	.272				

^aOxidized.

TABLE II. - SPECTRAL REFLECTANCE OF METALS

(a) Temperature, 294 K.

Wavelength, μm	Spectral reflectance											
	Aluminum	Copper	Gold	Molybdenum	Nickel	Platinum	Silver	Stainless steel 304	Tantalum	Tin	Titanium	Vanadium
0.330	0.808	0.206	0.309	0.416	0.340	0.541	0.274	0.453	0.386	0.569	0.135	0.397
.354	.823	.220	.312	.417	.355	.563	.623	.475	.406	.602	.145	.417
.377	.835	.229	.325	.420	.411	.581	.688	.500	.407	.648	.150	.427
.398	.840	.261	.337	.434	.435	.611	.748	.523	.420	.701	.167	.449
.415	.848	.290	.338	.450	.463	.626	.782	.536	.410	.716	.168	.455
.430	.851	.317	.336	.466	.476	.636	.803	.546	.410	.749	.177	.464
.444	.855	.334	.340	.480	.498	.645	.835	.563	.408	.761	.186	.462
.457	.864	.348	.338	.488	.508	.651	.831	.568	.403	.783	.192	.468
.470	.863	.383	.344	.500	.520	.663	.843	.583	.407	.791	.199	.475
.483	.869	.396	.353	.507	.530	.667	.856	.583	.398	.809	.208	.474
.497	.863	.410	.447	.506	.539	.688	.883	.586	.403	.812	.212	.473
.511	.865	.448	.585	.510	.554	.711	.893	.594	.397	.817	.218	.472
.525	.865	.455	.680	.505	.556	.710	.903	.598	.386	.821	.214	.468
.540	.863	.463	.749	.511	.566	.724	.888	.602	.387	.818	.213	.472
.554	.870	.494	.794	.506	.571	.720	.913	.616	.387	.824	.236	.470
.569	.871	.580	.824	.507	.583	.719	.906	.616	.384	.843	.240	.476
.584	.871	.701	.852	.508	.591	.720	.936	.625	.384	.832	.244	.477
.599	.877	.757	.873	.504	.601	.730	a.934	.627	.391	.830	.246	.471
.614	.870	.790	.890	a.519	.597	.721	a.940	a.624	.398	a.845	.250	a.472
.630	a.866	.784	a.902	a.520	a.613	a.737	.932	a.638	a.406	a.830	a.255	a.480
.647	a.872	.832	a.922	a.522	a.626	a.731	a.958	a.634	a.431	a.839	a.274	a.480
.665	a.876	a.840	a.929	a.530	a.626	a.743	a.957	a.640	a.460	a.836	a.275	a.484
.682	.881	.861	.946	.525	.635	.743	.977	.645	.490	.841	.281	.488
.701	.870	.869	.953	.545	.645	.770	.975	.651	.532	.835	.292	.489
.721	.876	.881	.943	.540	.647	.760	.984	.675	.564	.846	.297	.493
.743	.868	.848	.967	.535	.653	.765	.968	.670	.606	.853	.307	.500
.764	.860	.891	.967	.523	.655	.763	.963	.664	.632	.845	.320	.505
.788	.850	.898	.972	.535	.669	.762	.976	.666	.664	.840	.318	.501
.812	.849	.901	.968	.533	.671	.776	1.000	.671	.697	.824	.327	.504
.840	.834	.918	.973	.530	.674	.781	.983	.676	.720	.835	.336	.517
.868	.840	.918	.977	.540	.684	.778	.970	.680	.744	.824	.344	.510
.898	.873	.923	.980	.541	.684	.778	.978	.671	.772	.826	.333	.518
.929	.890	.945	.978	.557	.687	.778	.983	.684	.793	.840	.355	.528
.966	.914	.944	.990	.577	.660	.790	1.000	.676	.809	.820	.334	.518
1.003	.937	.940	.982	.602	.696	.805	.960	.695	.833	.824	.344	.523
1.045	.944	.949	.987	.636	.703	.801	.990	.700	.845	.820	.350	.530
1.085	.948	.960	.992	.723	.716	.816	.990	.699	.865	.815	.358	.542
1.130	.965	.957	.987	.769	.719	.810	.988	.695	.875	.815	.361	.562
1.180	.960	.960	.988	.789	.731	.808	.985	.720	.891	.820	.368	.572
1.240	.970	.975	.997	.775	.751	.815	.948	.720	.911	.839	.385	.612
1.300	.970	.970	.990	.779	.767	.822	.995	.726	.915	.853	.394	.620
1.380	.970	.971	.992	.824	.776	.820	1.000	.735	.933	.892	.402	.653
1.470	.984	.988	1.000	.870	.832	.850	1.000	.798	.961	.879	.433	.708
1.580	.988	.991	.995	.897	.850	.866	1.000	.814	.962	.905	.444	.733
1.710	.976	.980	.990	.881	.815	.826	1.000	.769	.949	.896	.441	.722
1.900	.971	.970	.985	.887	.810	.798	1.000	.756	.937	.891	.445	.723
2.160	.968	.975	.990	.906	.830	.812	1.000	.770	.948	.885	.461	.773

^a Average of photomultiplier and lead sulfide readings.

TABLE II. - Continued. SPECTRAL REFLECTANCE OF METALS

(b) Temperature, 373 K.

Wavelength, μm	Spectral reflectance											
	Aluminum	Copper	Gold	Molybdenum	Nickel	Platinum	Silver	Stainless steel 304	Tantalum	Tin	Titanium	Vanadium
0.330	0.823	0.208	0.321	0.529	0.352	0.540	0.315	0.448	0.391	0.565	0.133	0.412
.354	.829	.214	.321	.535	.376	.565	.686	.478	.403	.601	.140	.440
.377	.842	.228	.333	.537	.394	.588	.742	.502	.408	.643	.147	.436
.398	.838	.268	.347	.536	.435	.608	.799	.519	.434	.689	.161	.447
.415	.851	.279	.349	.543	.461	.631	.838	.540	.411	.714	.167	.465
.430	.861	.300	.346	.546	.481	.641	.848	.555	.415	.743	.171	.465
.444	.861	.324	.348	.554	.496	.644	.875	.566	.410	.766	.174	.469
.457	.850	.338	.348	.564	.514	.649	.876	.568	.411	.773	.182	.470
.470	.865	.358	.353	.570	.519	.671	.885	.580	.410	.785	.187	.474
.483	.864	.379	.373	.578	.534	.675	.896	.586	.407	.804	.195	.477
.497	.874	.403	.445	.574	.535	.685	.899	.591	.409	.805	.202	.471
.511	.870	.432	.562	.579	.554	.715	.930	.598	.419	.811	.212	.472
.525	.880	.442	.650	.571	.559	.709	.929	.600	.412	.820	.215	.470
.540	.871	.465	.727	.570	.565	.713	.928	.609	.407	.821	.221	.471
.554	.879	.496	.772	.571	.576	.710	.930	.615	.409	.822	.230	.471
.569	.875	.580	.811	.569	.576	.710	.932	.612	.401	.820	.233	.471
.584	.875	.684	.848	.567	.588	.716	.940	.616	.405	.826	.235	.479
.599	.880	.730	.865	.565	.595	.715	^a .942	.620	.406	.822	^a .238	.473
.614	.870	.785	^a .893	.570	^a .613	.723	^a .954	^a .628	.412	^a .831	^a .242	^a .478
.630	^a .882	^a .810	^a .898	^a .575	^a .614	^a .732	^a .944	^a .631	^a .426	^a .832	^a .247	^a .483
.647	^a .880	^a .827	^a .923	^a .574	^a .626	^a .736	^a .956	^a .636	^a .445	^a .838	^a .254	^a .485
.665	^a .882	^a .848	^a .938	^a .576	^a .625	^a .740	.954	^a .636	.468	^a .848	.256	^a .483
.682	.884	.861	.947	.584	.641	.751	.961	.640	.498	.839	.261	.486
.701	.874	.880	.944	.580	.650	.745	.962	.651	.537	.834	.268	.490
.721	.879	.890	.962	.576	.662	.770	.962	.671	.560	.842	.280	.494
.743	.877	.891	.963	.584	.670	.760	.968	.652	.600	.843	.285	.495
.764	.874	.866	.963	.580	.660	.759	.968	.663	.622	.861	.294	.501
.788	.870	.900	.975	.580	.660	.770	.971	.670	.666	.840	.304	.505
.812	.855	.917	.973	.582	.680	.775	.980	.673	.683	.846	.310	.510
.840	.853	.924	.976	.586	.675	.795	.975	.671	.708	.830	.318	.487
.868	.859	.924	.973	.589	.680	.775	.975	.673	.738	.836	.322	.519
.898	.873	.938	.978	.585	.691	.787	.966	.680	.765	.839	.332	.529
.929	.878	.950	.984	.588	.689	.787	.975	.681	.788	.844	.334	.514
.966	.906	.949	.980	.628	.688	.798	.979	.684	.801	.834	.340	.538
1.003	.924	.952	.988	.641	.707	.799	.976	.690	.825	.821	.344	.535
1.045	.934	.950	.982	.667	.715	.794	.970	.689	.838	.827	.352	.539
1.085	.950	.959	.983	.701	.714	.790	.970	.697	.851	.834	.352	.551
1.130	.952	.965	.989	.721	.729	.806	.965	.700	.868	.832	.363	.551
1.180	.955	.963	.991	.754	.736	.805	.979	.708	.883	.830	.362	.596
1.240	.970	.972	.996	.804	.755	.831	.985	.721	.896	.849	.382	.611
1.300	.971	.971	.988	.822	.755	.823	.976	.726	.901	.851	.388	.625
1.380	.971	.979	.995	.840	.775	.832	.976	.732	.921	.858	.405	.650
1.470	.979	.983	.985	.878	.790	.845	.990	.771	.920	.890	.433	.658
1.580	.983	.988	.994	.956	.820	.866	.988	.776	.940	.891	.445	.685
1.710	.974	.985	.995	.904	.804	.807	.987	.765	.936	.894	.438	.715
1.900	.970	.980	.983	.905	.806	.802	.975	.760	.931	.898	.445	.726
2.160	.970	.985	.982	.918	.830	.820	.980	.769	.935	.905	.455	.768

^aAverage of photomultiplier and lead sulfide readings.

TABLE II. - Continued.

(c) Temperature, 473 K.

Wavelength, μm	Spectral reflectance											
	Aluminum	Copper ^a	Gold	Molybdenum	Nickel	Platinum	Silver	Stainless steel 304	Tantalum	Tin	Titanium	Vanadium
0.330	0.798	0.250	0.332	0.518	0.346	0.565	-----	0.402	0.364	0.483	0.133	0.375
.354	.808	.268	.324	.508	.369	.591	.583	.359	.382	.533	.141	.393
.377	.810	.288	.330	.513	.392	.609	.635	.377	.388	.573	.147	.406
.398	.820	.314	.346	.519	.430	.622	.696	.402	.398	.620	.157	.421
.415	.836	.325	.350	.526	.454	.647	.718	.426	.401	.648	.164	.433
.430	.845	.339	.346	.537	.470	.658	.745	.446	.402	.682	.168	.438
.444	.843	.350	.358	.544	.486	.655	.765	.460	.401	.698	.174	.443
.457	.851	.365	.356	.546	.496	.663	.771	.475	.398	.712	.178	.447
.470	.849	.377	.356	.554	.503	.675	.788	.488	.401	.729	.184	.453
.483	.862	.387	.382	.562	.521	.686	.805	.503	.400	.735	.192	.456
.497	.878	.387	.446	.574	.534	.705	.820	.518	.407	.758	.197	.468
.511	.891	.385	.563	.594	.565	.693	.840	.541	.417	.768	.208	.462
.525	.880	.377	.640	.585	.563	.706	.845	.547	.410	.778	.213	.466
.540	.890	.370	.711	.580	.576	.708	.857	.553	.407	.778	.218	.469
.554	.890	.377	.752	.580	.577	.710	.862	.560	.408	.791	.220	.469
.569	.875	.388	.790	.567	.581	.711	.868	.565	.409	.778	.224	.470
.584	.880	.398	.823	.563	.586	.724	.871	.573	.412	.787	.232	.468
.599	.869	.395	.860	.561	.591	.721	.879	.577	b.410	.792	b.233	.462
.614	b.868	.399	b.867	b.566	b.605	b.738	b.890	b.584	b.422	b.796	b.236	b.472
.630	b.881	.388	b.880	b.565	b.608	b.735	b.890	b.591	b.426	b.791	b.244	b.468
.647	b.879	.385	b.905	b.566	b.618	b.741	b.912	b.596	b.440	b.792	b.248	b.485
.665	.873	.373	.911	.566	.624	.755	.919	.606	.455	.783	.256	.473
.682	.870	.371	.925	.560	.620	.754	.926	.607	.473	.800	.264	.477
.701	.877	.385	.921	.572	.630	.755	.935	.620	.495	.797	.269	.478
.721	.860	.399	.925	.570	.650	.764	.936	.621	.525	.803	.275	.486
.743	.871	.423	.935	.574	.641	.765	.946	.625	.553	.807	.278	.485
.764	.872	.443	.945	.574	.655	.764	.942	.632	.573	.813	.290	.494
.788	.860	.474	.948	.568	.653	.779	.938	.640	.608	.805	.296	.488
.812	.857	.503	.955	.568	.648	.782	.955	.643	.634	.803	.302	.497
.840	.845	.544	.951	.571	.667	.793	.960	.646	.656	.812	.309	.503
.868	.864	.581	.955	.583	.671	.789	.960	.651	.685	.802	.316	.505
.898	.869	.620	.964	.590	.665	.790	.965	.653	.707	.801	.321	.513
.929	.872	.628	.962	.600	.684	.790	.970	.667	.728	.798	.329	.521
.966	.905	.671	.956	.615	.689	.794	.970	.670	.746	.816	.332	.522
1.003	.902	.706	.950	.632	.690	.795	.967	.673	.766	.805	.339	.535
1.045	.918	.735	.975	.664	.710	.795	.973	.677	.779	.814	.346	.537
1.085	.930	.763	.973	.687	.714	.806	.973	.678	.795	.807	.352	.542
1.130	.932	.797	.968	.720	.721	.807	.968	.684	.811	.808	.361	.559
1.180	.943	.818	.974	.742	.720	.810	.974	.691	.829	.811	.367	.572
1.240	.951	.861	.970	.791	.742	.813	.977	.702	.846	.822	.381	.598
1.300	.950	.875	.963	.804	.749	.806	.970	.707	.855	.817	.394	.617
1.380	.953	.900	.961	.829	.764	.812	.970	.717	.864	.824	.399	.636
1.470	.952	.921	.957	.854	.774	.804	.966	.726	.878	.824	.423	.657
1.580	.952	.923	.970	.870	.790	.805	.970	.738	.891	.844	.428	.639
1.710	.943	.937	.971	.884	.790	.791	.971	.733	.881	.838	.428	.690
1.900	.940	.935	.962	.884	.787	.800	.969	.737	.890	.847	.434	.705
2.160	.935	.942	.956	.894	.800	.821	.965	.749	.890	.845	.461	.723

^aAverage of photomultiplier and lead sulfide readings.^bSample oxidized.

TABLE II. - Concluded. SPECTRAL REFLECTANCE OF METALS

(d) Maximum temperature points.

Wavelength, μm	Spectral reflectance			
	Aluminum (573 K)	Gold (573 K)	Molybdenum (540 K)	Platinum (528 K)
0.330	0.809	0.368	0.401	0.584
.354	.820	.358	.405	.587
.377	.850	.356	.414	.602
.398	.865	.364	.437	.630
.415	.861	.372	.450	.640
.430	.876	.374	.461	.650
.444	.875	.374	.475	.660
.457	.880	.379	.485	.673
.470	.885	.384	.491	.682
.483	.891	.414	.500	.685
.497	.886	.464	.506	.697
.511	.900	.550	.530	.720
.525	.900	.636	.527	.725
.540	.899	.707	.525	.720
.554	.897	.755	.532	.731
.569	.908	.795	.521	.725
.584	.907	.831	.525	.732
.599	.914	^a .856	^a .527	^a .734
.614	^a .914	^a .878	^a .526	^a .740
.630	^a .912	^a .886	^a .526	^a .739
.647	^a .901	^a .905	^a .532	^a .742
.665	.903	.915	.538	.745
.682	.890	.926	.533	.756
.701	.900	.931	.545	.749
.721	.892	.931	.542	.754
.743	.880	.943	.547	.764
.764	.885	.944	.551	.771
.788	.869	.947	.545	.775
.812	.875	.953	.551	.778
.840	.870	.961	.550	.774
.868	.874	.957	.555	.781
.898	.869	.965	.560	.780
.929	.876	.970	.584	.790
.966	.903	.964	.597	.788
1.003	.901	.975	.616	.798
1.045	.914	.973	.637	.800
1.085	.920	.974	.665	.798
1.130	.929	.970	.689	.799
1.180	.940	.972	.714	.805
1.240	.945	.977	.772	.806
1.300	.950	.975	.778	.807
1.380	.951	.970	.811	.805
1.470	.960	.971	.820	.810
1.580	.960	.970	.838	.801
1.710	.951	.970	.856	.798
1.900	.944	.958	.874	.799
2.160	.947	.961	.895	.821

^aAverage of photomultiplier and lead sulfide readings.

